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LANGUAGE AFTER SECTION OF THE CEREBRAL COMMISSURES[1]

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INTRODUCTION

SOME of the functional effects that appear in man following surgical separation of the hemispheres produced by complete transection of the corpus callosum plus the anterior and hippocampal commissures, with separation of the massa intermedia have been described in earlier reports (Gazzaniga, *et al.*, 1962, 1963, 1965). The observations were based on two patients operated on by Drs. Philip Vogel and Joseph Bogen of the California College of Medicine at the White Memorial Medical Center in Los Angeles for relief of intractable seizures. In general the post-surgical studies indicate a striking functional independence of the gnostic activities of the two hemispheres. Perceptual, cognitive, mnemonic, learned and volitional activities persist in each hemisphere, but can proceed separately in each case outside the realm of awareness of the other hemisphere. The subjective experience of each hemisphere is known to the other only indirectly through lower level and peripheral effects.

This disruption of interhemispheric integration produces remarkably little disturbance in ordinary daily behaviour, temperament or intellect. The functional deficits tend to be compensated by the development of bilateral motor control from each hemisphere, also by bilaterality in some

[1]Aided by U.S. Public Health Service grant MH 3372 and the Frank P. Hixon Fund of the California Institute of Technology. All subjects examined were patients of Drs. Philip Vogel of the California College of Medicine and Joseph Bogen of the Ross Loos Medical Group, Los Angeles. We are also grateful to Dr. Joseph Bogen for his continuing interest and co-operation in carrying out the language studies.

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of the sensory projection pathways and by a variety of other unifying factors that we deliberately avoid or exclude so far as possible in the testing procedures. Ordinarily there would seem to be a large common denominator of similar and closely related background activity in right and left hemispheres.

This paper describes some of the further findings obtained to date with reference specifically to language functions. As might be expected, it is in activities involving language and especially speech, that the effects of sectioning the cerebral commissures become most conspicuous. It is the severing of connexions that link the minor hemisphere to the speech centres in the major hemisphere that is directly responsible for many of the more pronounced functional disturbances.

General Background

Three patients from a total of six who have undergone the surgery are included in the present study. All three have been virtually free of seizures since their surgery for four, two-and-a-half and one years respectively to date. Three others have had various complications and have shown little or no improvement over the pre-operative condition. The medical case histories of two of those included here have already been described (Bogen and Vogel, 1962; Bogen *et al.*, 1965). Both these persons have continued to give full co-operation in functional testing. A third case (L. B.) from the same series who, like the others, had undergone a similar disconnexion of the hemispheres for the same reason, is included here. The surgeons were confident in this case that both fornices and all main cortical veins draining into the sagittal sinus had been spared. This third patient, a right-handed 12-year-old boy, had no history of traumatic brain injury. He was a bright, affable and generally happy individual with a pre-operative I.Q. of 115 (WISC)[1] scored under anti-convulsant sedation. Pre-operative testing of the visual fields, somatic sensibility and motor co-ordination disclosed no significant abnormalities.

The language capacity of the minor hemisphere in Case 1 proved to be almost negligible and was decidedly inferior to that of the other two subjects. Also, Case 1, unlike the others, had sustained considerable brain damage, especially in the minor hemisphere, prior to surgery. For these reasons it was assumed that findings in Cases 2 and 3 could be relied upon to reflect more accurately the typical effects of cerebral disconnexion *per se*, whereas Case 1 is more representative of the kinds of disconnexion syndrome seen in cases of brain tumour, vascular accidents, or other cerebral pathology.

[1]Administered by Mrs. E. Gunther, Hacker Clinic, Los Angeles.

OBSERVATIONS

Early Recovery

The most rapid recovery was seen in the third and youngest patient. During the first twenty-four hours after surgery this boy was conversing with the hospital staff with good comprehension, made quips about having a "splitting headache," and was able to recite "Peter Piper picked a peck of pickled peppers," etc. rapidly with no apparent difficulty. From his comments and his general attitude in the intensive care unit, it seemed evident that the same humour, mannerisms and general personality that characterized this person pre-operatively were already present from the first day after surgery.

By the second day he was feeding himself, consuming normal portions of solid food. He was walking around the hospital at the end of the first week, and earlier mobility would probably have been possible, had it been permitted. At this time he also displayed only a little of the apraxic difficulty in making voluntary movements with the left hand to verbal command that had been so marked for months in Case 1 and for weeks in Case 2. What little inability he had in this regard involved the individual control of the left fingers. Shoulder, elbow and wrist movements all could be made at will or to verbal command, and he was able upon request to make a closed fist moving all fingers together. The left fingers could be controlled individually at this stage if the verbal command was accompanied with an overt "do this" type of demonstration. Case 3 was discharged three weeks following surgery. During the next two months general somatosensory and visual testing showed a course of recovery almost identical to that described for Case 2 (Gazzaniga *et al.*, 1965) with the time scale somewhat advanced by almost two months.

A short period of mutism followed the surgery in the other two cases lasting for approximately thirty days in Case 1 and one to two days in the second patient. Case 2, a 30-year-old housewife and mother, was talking over the telephone on Day 3 and was walking with assistance and feeding herself at the end of the first week. During the first two weeks after surgery she displayed an erratic emotional lability in her conversation. At one moment, for example, she would be conversing in a normal manner. Suddenly and for no apparent reason, she would be on the verge of tears while, however, keeping the main train of thought. Then just as abruptly she would resume talking in a normal manner. During the same two week period she was also prone to confabulate a good deal during interviews—especially with the onset of fatigue. It was considered highly probable that part or all of her right fornix had been divided in the surgery.

During this period Case 2 displayed good memory for many of her pre-operative experiences up to and including her hospitalization for the surgery. On Day 4 she acknowledged and appeared to recognize from

among a group of strangers someone whom she had seen only briefly on the second day before surgery. She was able, during the first week after surgery, to hum with good tonal quality several of her old favourite tunes. Complaints that her memory was poor were received from the family, however, for about four months following the surgery.

In Case 1, a 48-year-old right-handed male payroll clerk, speech reappeared after one month and had returned to approximately normal so far as ordinary conversation was concerned by about the eighth week. At this time there appeared to be no change in gross temperament or intellect in this person, and he repeatedly remarked that he hadn't felt better in years—probably attributable in part to the reduction in medication that proved to be possible after the surgery.

After these persons were well recovered from surgery and had again settled into their routines at home, more detailed lateralized tests were started including those described below aimed at determining among other things the extent to which speech and language had been preserved in each of the disconnected cerebral hemispheres. The positive findings reported below were evident starting from about the fourth month for Case 2 and the second month for Case 3. Prior to this function seemed to be depressed below the normal level presumably from disruption of the tonic influence of the corpus callosum and other diaschistic effects.

In the following tests and their interpretation we take for granted some of the basic findings already reported, such as the absence of any interchange of cognitive experience or any transfer of learning or memory from one hemisphere to the other (Gazzaniga *et al.*, 1962, 1963, 1965). In view of the evidence for independent mental function in the two disconnected hemispheres, it makes for confusion to try to describe the behaviour and cerebral symptoms with reference to the individual person in the ordinary way. Accordingly we continue the practice of referring specifically to the perceptual, cognitive and other mental functions of each hemisphere independently. We also take the position for reasons reviewed elsewhere (Sperry, 1964, 1966; Sperry and Gazzaniga, 1965) that conscious awareness is commonly present in the minor as well as in the major hemisphere and that the two separate spheres of conscious experience may proceed concurrently as well as in alternation.

Language Expression

Speech

In tests aimed to determine the capacity to speak with reference to information specifically lateralized to one or the other hemisphere, very different results were obtained for the right and left sides. Whereas spoken descriptions of stimulus material and other verbal responses obtained from the left hemisphere showed from the beginning little or no impairment, the right hemisphere appeared in similar testing to be totally

incapable of speech. For example, visual stimuli such as numbers, letters, words and pictorial material presented tachistoscopically in the right visual half field at one-tenth second as described elsewhere (Gazzaniga *et al.*, 1965) were reported correctly and described normally.

The same was true for stimuli presented to the right hand with vision excluded. A familiar item placed in the subject's right hand, like a spoon, knife, comb, toothbrush, block letters, or any of a series of simple geometric shapes were readily recognized, named and described by both subjects. Speech was also used with normal facility in making various somatosensory discriminations involving weight, pattern, and temperature applied anywhere on the right half of the body. This was true as well for the left side of the face and head, and we have assumed this to be correlated with the presence of an ipsilateral component in the afferent projections of these areas to the left hemisphere. In short, any sensory information entering the left hemisphere, or the results of the central processing of that information, could be reported through speech in much the usual manner.

Conversely, both subjects were totally unable to give accurate spoken reports for even the simplest kind of sensory information projected to the right hemisphere. Test material presented to the left hand or to the left half of the visual field evoked in each case only irrelevant confabulatory spoken responses or none at all. For example, a pencil placed in the left hand might go unnoticed and elicit no verbal comment whatever, or more typically, its presence would be recognized but it would be called a "can opener" or a 'cigarette lighter," etc. Such guesses came presumably from the left dominant hemisphere and were based on whatever indirect cues happened to be available to that hemisphere. All visual stimuli flashed to the left half field similarly went undescribed or were reported vocally, as just a "flash" or a "white flash." Whereas Case 1 had been unable to localize verbally points of stimulation on the left side of the body below the neck, Cases 2 and 3 had little trouble in reporting verbally the correct localization of cutaneous stimuli applied to the left side of the entire body, excepting only the hands and feet. This again seems best attributed to bilateral cerebral projection of sensory cues for cutaneous and deep local sign including an ipsilateral component to the major hemisphere, that is particularly strong in the case of the face and head.

Writing

The right hand with its main motor control centred in the left hemisphere along with speech was always capable of writing correctly the names and descriptions of visual or tactile stimuli presented to the left hemisphere with no special difficulty evident. When the same stimulus material was presented to the right hemisphere, however, none of the stimuli could be described or named in writing by any of the patients using either hand. For example, when a spoon or a knife was placed in the left

hand, or a picture flashed to the left visual field, any written responses seemed to represent mere guesswork by the major hemisphere. Writing to dictation posed no problem for these persons when they were using the right hand.

Some simple writing to dictation was possible with the left hand also after the seventh month in Case 2 and after the first month in Case 3, but not at all in Case 1. This performance with the left hand seems best ascribed to the bilaterality in motor control. This ability of each hemisphere to govern movement of the ipsilateral as well as the contralateral limb showed definite improvement in all cases during the post-surgical observation period. That the writing with the left hand was directed from the major and not the minor hemisphere is shown by the above-mentioned inability to write when the stimulus is strictly lateralized to the right hemisphere. Further, the name of an object flashed to the left hemisphere could be written with the left hand in the absence of audible or other intermediary cues. The left arm writing was guided more easily from the proximal joints than from the fingers.

Drawing

Although not language, expression of understanding by drawing is closely related to some of the foregoing and is included here for comparison. None of the patients had a highly developed talent for drawing pictures prior to surgery, although Case 3 at 12 years had some favourite caricature sketches that he did moderately well and he was able to repeat the same sketch upon request. This capacity to sketch his favourite caricature with free hand use was severely impaired during the first several months following surgery, but then improved with the right hand to almost its former level. The drawing capacity of the two older patients after surgery was decidedly poor even with the preferred right hand suggesting that cerebral interaction through the commissures may have some particular importance for artistic drawing in the normal brain.

Within their reduced artistic limits, each patient was able to reproduce by drawing with the right hand various geometric figures like triangles, parallelograms, trapezoids, stars and other line drawings presented to the right visual half field. They could do the same for familiar objects like a comb, fork and alphabet letters presented out of sight for palpation and stereognostic exploration by the right hand. And they could draw with the right hand simple objects and patterns named vocally by the experimenter. When stimulus material was presented to the right hemisphere via the left hand or in the left half visual field, Cases 2 and 3 were both able to make recognizable reproductions of very simple material using the left hand. For example, flat wooden cut-outs including a circle, square, triangle, toy alphabet letters and other simple shapes could be drawn after having been explored by the left hand. This contralateral performance,

controlled from the minor hemisphere, however, was generally inferior to that of the right hand in response to stimuli presented exclusively to the left hemisphere.

When the subjects were shown three-dimensional forms like the Necker cube, a house, or other objects involving more complex spatial relations and asked to reproduce them, their performance with the left hand was consistently superior to that with the right so far as getting correct spatial representation was concerned, as described earlier (Gazzaniga *et al.*, 1965; Bogen and Gazzaniga, 1965).

Ideation in the Absence of Linguistic Expression

With regard to the major hemisphere there was little reason to question the preservation of thought, imagination, reason, judgement and other cognitive functions since these were amply demonstrated in conversation and behaviour generally as well as in the testing situation. Scores on the WISC I.Q. tests at two to three months after surgery were not significantly lower than those obtained before surgery when one omitted test items requiring use of the left hand. That the surgery has produced at least subtle impairments in some of these higher cognitive functions, however, can neither be asserted nor denied at this time without more refined and specific testing of these factors than we have attempted to date.

In regard to the minor hemisphere, on the other hand, even the approximate level and quality of cognition remained highly obscure from the beginning. The inability of this hemisphere to express itself in speech or writing, and the apparently low, but uncertain, level of comprehension for verbal material, as indicated below, made any assessment of the mental capacity of the minor hemisphere difficult and devious. With respect to the total picture of the functional effects of the surgery, the cognitive properties of the speechless and agraphic minor hemisphere has always posed the outstanding and most challenging unknown. Accordingly our main testing efforts were directed at this problem. A variety of related questions are involved here that concern possible interrelations between the development of language and cognition.

When stimulus material was presented to the minor hemisphere, under conditions in which its comprehension could be indicated by purely nonverbal responses, it became evident that the mute minor hemisphere was quite capable of perceptual understanding and of forming ideas or concepts that went well beyond a mere image of the stimulus. Not uncommonly these test performances seemed to involve some abstraction, generalization and mental association. This was demonstrated, for example, in tests that combined the presentation of visual pictures to the right hemisphere followed by the retrieval of a matching object with the left hand using the sense of touch. The subjects were able on the first exposure to match such disparate stimuli as a crude ink drawing of a

skeleton key presented visually with a very differently shaped car key selected by touch. Similarly when a picture of a wooden match was presented, they retrieved correctly a book of paper matches and so forth. Both visual and tactile stimulation had to be in the same hemisphere; cross-integration of these inter-modal tasks failed consistently. Similar performances were described in connexion with tests for vision (Gazzaniga, *et al.*, 1965) and many others are given below in tests for symbol comprehension.

Other examples of ideation in the absence of linguistic expression were obtained within the somatosensory sphere in which recognition and retrieval tests were performed with the left hand, vision and audible speech being excluded. Following presentation of a sample object to the left hand for stereognostic recognition, the left hand might then search for a considerable time, up to a half-minute or more, among a series of other objects before coming to and selecting the correct one. Some of the incorrect objects, especially those most resembling the correct item, might be lifted and explored at length before being rejected. When additional delay periods were imposed as part of the task in this situation, remembrance of the stimulus object could be held for periods of time exceeding one minute. This was true for Case 3 even when distractions were introduced during the delay, such as irrelevant conversation, and asking the patient to walk out of the room, down the hall, and back. After picking out the correct item at the end of such a delay period, the verbal response of the subjects, when questioned, indicated that the major hemisphere had no idea what the object was that had been perceived and remembered by the right hemisphere. The proficiency of Cases 2 and 3 on these tasks far exceeds that described earlier in Case 1 in which the minor hemisphere had sustained extensive damage ten years prior to the surgery. The upper limit of such delayed-reaction capacities has yet to be determined.

Language Comprehension

The findings throughout the foregoing are consistent with the inference that language functions had survived with little, if any, impairment in the left, major hemisphere. Conversely, the same tests suggest the possibility of complete absence of any language development in the minor hemisphere, in that correct responses were unobtainable for the simplest of words, numbers, or even single letters when these were presented solely to the right hemisphere. In tests like the foregoing the minor hemisphere appears to be alexic, word blind, word deaf, agraphic and astereognostic (for review, *see* Geschwind, 1962, 1965). The question of the extent to which language is represented in the subordinate hemisphere has long been a matter of controversy with authoritative proponents supporting both sides of this issue (*see* Zangwill, 1962). The tests that have been described

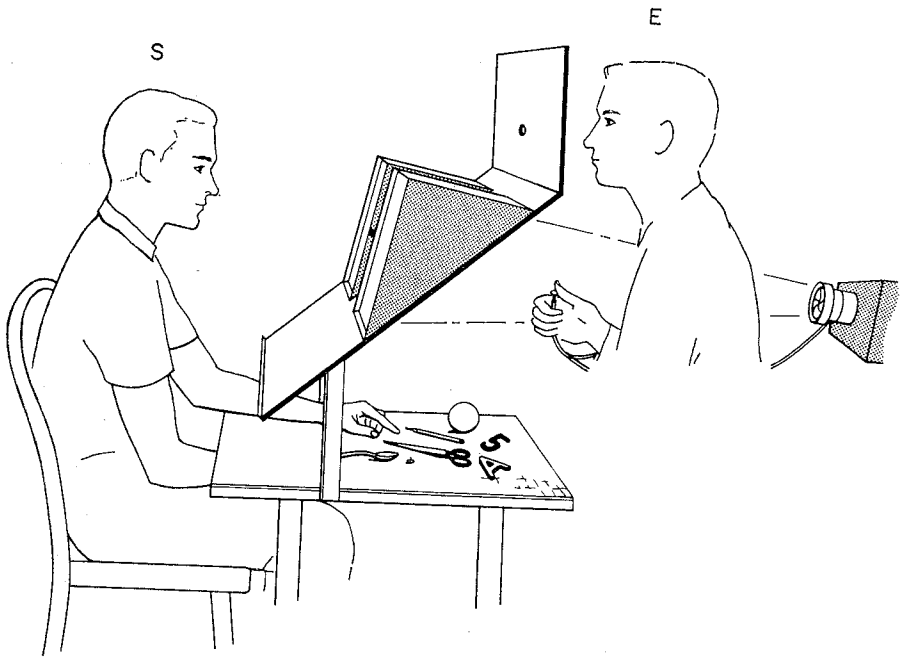
thus far in the present study required in addition to perception and comprehension of non-verbal stimulus material only an ability to use language at most for the expression and communication of this understanding. It thus remained possible that the minor hemisphere was capable of some recognition and comprehension of language and other symbolic information but that this comprehension had not been evident for lack of any means for expression.

To investigate the possibility of this we applied tests that were designed to separate the comprehension of language from its expression. The motor activity in these tests was non-verbal and depended in most instances upon pointing with the left hand to a correct answer presented as one item among an array of incorrect items. Even these tests failed to reveal any significant language comprehension in the damaged right hemisphere of Case 1. In the other two cases, however, in which prior brain damage had been absent or minimal, it was possible to demonstrate comprehension of verbal and other symbolic material presented visually, audibly or tactually as outlined in the following.

Visual Comprehension

Both Cases 2 and 3 proved to be capable of reading letters, numbers and short words in the left visual field. For example, when the names of familiar objects were flashed at one-tenth second to the left field, the subject though unable, as described above, to give a correct verbal response, was nevertheless able to retrieve the matching item from among a series of 10 objects laid out in open view in front of him. If words such as *cup, knife, pen, orange*, etc., were tachistoscopically presented in the left visual field, in the set-up illustrated in fig. 1, the patient could also readily point out the correct one from among 10 items arrayed in free view before him. Similarly, if a picture, for example, of a ship, were flashed into the left visual field, these subjects would verbally deny having seen anything. When urged to let the left hand try, however, they would then proceed to pick up the card with "ship" written on it from a series of 10 laid out in open view in front of them. It was difficult to determine the upper limits of such comprehension under these conditions because the choice of stimulus material was restricted to what could be read in the brief exposure time required to avoid eye movement.

The same sort of result was obtained in tasks that required intermodal integration going from vision to touch and vice versa. When a sample word such as pencil, tack, knife, sock, comb, etc., was presented in the left visual half field, the left hand, *but not the right*, could be used to search out the described correct matching object by touch from among an array of others, all shielded from vision. In such instances, when the stimulus and the matching answer were both presented exclusively to the right hemisphere, the subjects remained completely unaware of the given stimulus



Testing apparatus: Slanting shield on table prevents subject from seeing test items on table, his hands, or the examiner. It contains ground glass viewing screen for back projection of 2 × 2 slides, and also serves to hold cards or other test items set before subject in free view. Examiner flashes slides when subject's gaze is seen to be properly centred on designated fixation point. A second examiner beside subject records trials and subject's reactions.

and response selection in their dominant conversant hemisphere. After making a correct manual response through the mute hemisphere they would commonly describe the selected object as some totally unrelated item that was obviously a pure guess. Where the objects for choice were laid out where both hemispheres could see them, the speech hemisphere would routinely confabulate after the fact, and state that a particular word had been seen to fit the object to which the left hand already had pointed. Under the latter conditions they would guess correctly the word that had been projected to the minor hemisphere but often the guesswork in the dominant hemisphere was revealed in the subject's use of a synonym that did not have even remote resemblance in spelling.

Comprehension of Spoken Words

Because of the bilaterality of auditory afferent projection, tests for the comprehension of words presented audibly to the right hemisphere were run, not by trying to lateralize the original input, but by limiting the

available answers exclusively to the right hemisphere. In one test situation the patients were required to push a response button held in the left hand, when they saw that one of a series of five nouns projected in serial succession to the left visual field, matched the test word spoken previously. They were able to do this and also to pick out the correct word from among a series presented to the left half field that fitted a descriptive phrase read aloud by the examiner. For example, the examiner would read, "Used to tell time," and would then flash five choice words in succession to the left visual field. In this instance the patients made a correct manual signal to the word "clock." When one of them was asked in passing what word he had seen, the reply (from the major hemisphere) was "watch." Here again was another demonstration of what we constantly encounter in testing these persons, namely, complete agnosia in one hemisphere for cognitive experiences that have just transpired in the other hemisphere.

Comprehension of the spoken word by the minor hemisphere was further shown by the patients' ability to retrieve by blind palpation with the left hand an audibly named object from among an array of objects presented to the left hand. The patients for example had no problem retrieving a safety pin when it was presented along with: *ring*, *coin*, *sock*, *tack*, *marble*, *pencil*, *pen*, *flashlight bulb*, and *spoon*. This was true also for a group of geometric solids as well as other series of objects all made of the same material and all of approximately the same weight to exclude any possible cues such as sound or weight, etc.

Comprehension Through Stereognosis

For the detection of latent linguistic and other symbolic mental functions in the aphonic non-communicative hemisphere, tests based on tactile input from the left hand were found to have certain advantages. There was no need, for example, to limit the presentation of the test material to a brief exposure of a fraction of a second as with vision. The subject could take time to explore the stimuli and the complexity of the test material could be increased accordingly. Also, competitive function in the other hemisphere could be reduced more effectively by elimination of non-specific visual and auditory distractions which is more difficult to achieve with visual and auditory testing. As with visual and unlike auditory material the perceptual process in the case of stereognosis can be confined to a single hemisphere.

The tests involving stereognosis were carried out in the general testing apparatus illustrated on page 140. The slanting screen served to exclude vision of the hand and arm and the test objects. The eyes were closed for difficult tasks to aid concentration on the performance with the left hand. Also, the table was covered with acoustic soundproofing material to exclude auditory cues in manipulation of the objects which the subjects'

major hemisphere was very quick to use to facilitate guessing the correct response. Preliminary testing of Case 3 confirmed the findings in the earlier cases with respect to the more generalized features of stereognosis following forebrain commissurotomy. Stereognosis was approximately normal for each hand in Case 3 so long as the motor response was through the same hand, i.e. by motor demonstration of how the test object is used, by retrieval through touch of the same item from among others, or by pointing to matching pictures, etc. Cross-matching or cross-comparison of stereognostic discriminations from one to the other hand failed consistently in all cases. All three subjects have always been unable to describe verbally or in writing any stereognostic discriminations made through the left hand. Only the presence or absence of a stimulus and very gross differences of localization and in the direction of movement of a stylus across the left hand were detectable by the speaking hemisphere. In short, practically all stereognostic discriminations made with the left hand were processed entirely by the right hemisphere and vice versa.

Tasks that depended upon stereognosis in the left hand could, therefore, be used to investigate the perceptive capacity of the minor hemisphere. For example, the ability to use the left hand to search out by touch an object described by spoken or written words could be taken to mean that there must have been comprehension of those words within the minor hemisphere. This presumes the exclusion of indirect sophisticated strategies of various sorts that seemed to be ruled out under our present testing conditions. Conversely, after a test object had been perceived solely by the left hand, the ability to select a correct audible or written name for that object could also be taken as evidence of comprehension of those words in the minor hemisphere. A large battery of tests designed along these lines was applied to subjects 2 and 3 with results in both cases that further confirmed the conclusion that there is considerable comprehension of language present in the minor hemisphere despite the incapacity of this hemisphere for motor expression.

A series of 10 objects was placed one at a time in the subject's left hand out of sight behind a screen and a printed list of the 13 names of the test objects was set up on a card in front of the subject for free visual inspection. Both subjects, after having felt each of the 10 items in scrambled order, were able then to point correctly to the name of the given item in the printed list. A large variety of everyday items were correctly identified under these conditions. Typically the subjects would spontaneously offer the correct name by saying it aloud, but only after the left hand had first pointed correctly, never before. If asked to point to the name of an object with the right hand while feeling it with the left hand, they sometimes could do so especially if the names were individually placed 6 to 12 inches or more apart. However, apraxia in the form of hesitancy, false moves, and outright errors of response were not uncommonly seen under these

conditions. Frequently, after an error had been made with the right hand, the left hand would then jerk up spontaneously from under the screen to point to the correct answer. Confusion in the right hand control was potentiated under these conditions by conversation with the subject, presumably by bringing in the left hemisphere.

Under similar testing conditions the subject was asked to signal the correct name of the test object held in the left hand by raising the hand at the proper time when a list of names was read aloud by the experimenter. Comprehension of spoken words similar to that shown for written words above was clearly demonstrated. These two types of tests were extended from simple nouns into verbs, adjectives and phrases of different categories. There is almost no limit to the variety and refinement that could be introduced into such tests more thoroughly to analyse in detail the language capacity of the speechless hemisphere. Samples of some of the more complicated test words for which some recognition and understanding seemed to be present in the right hemisphere are listed as follows:

> rough, smooth, round, cone, rectangle, cylinder, square, pyramid, flashlight bulb, tweezers, safety pin, measuring instrument, door latch, clown, Indian, etc.

In other tests a definition was first read aloud by the examiner after which the subject then explored blindly a series of objects with the left hand feeling for an item that would satisfy the examiner's definition. By careful selection of words of increasing difficulty in the spoken definition, this type of test also was extremely informative and could be extended over a wide range even though the test objects themselves remained fairly simple. Under the same conditions, the definitions, names, descriptive words, phrases and adjectives could be written out for free visual, instead of auditory, presentation.

In similar tests, the linguistic cues for comprehension and retrieval by stereognosis were flashed tachistoscopically to the left half visual field. Only simple short, usually single, words could be used with this form of presentation. On the other hand, this procedure gave the greatest assurance that the left hemisphere was not contributing to the performance. The words were printed vertically in some cases as well as horizontally and presented near the vertical mid-line on the left side in order to utilize central vision as much as possible. When words like *coin, ball, apple, comb*, etc. were flashed to the right hemisphere the subjects were able to search out the item named by palpating blindly with the left hand. They were asked what the item was on occasional trials after a correct selection had been made and while the item was still in the left hand but out of sight behind a screen. If the item were named correctly, as happened very rarely, the trial was thrown out on the supposition that the eyes had probably moved from the fixation point at the time of exposure and had allowed the test

word to be projected to the left hemisphere. With these rare exceptions it was clear from the verbal responses that the left hemisphere was only guessing and that knowledge of the correct answer had been confined to the right hemisphere.

Spelling

Tests were run to find out to what degree the right hemisphere might have the ability to order and arrange individual letters into words. Alphabet letters about four inches high cut from heavy cardboard were presented out of vision to the left hand for manual palpation and arrangement. Thus the patients had only to feel and recognize the individual letters and then place them in correct spatial order from left to right. Case 2 failed to perform convincingly, but the significance of this was questionable in view of the left-handed hypesthesia. Only Case 3 was able to spell consistently with the subordinate hemisphere as indicated in results like the following: The subject was told to spell a word like "dog," after which the examiner placed the appropriate three letters, one at a time in random order, into the subject's left hand for placement on the table. Very simple familiar words like *the*, *how*, *what*, *pie*, *hat*, were spelled correctly under these conditions but only slowly and with considerable effort. When an occasional mistake was made in letter order, the examiner would suggest that the subject check the word, and usually the error was found and corrected on the first such check. During this particular test wherein the left hemisphere also heard, the subject would often talk in a confabulatory way. Thus while holding the "O" for "dog" in his left hand the subject would say, "That's the 'D'." Nevertheless the left hand would continue to spell correctly, demonstrating the ability of the minor hemisphere to maintain its own reasoning, will and intent in the presence of competitive ideas and other distracting influences from the major hemisphere.

In further tests, a group of three or four letters was presented out of vision to the left hand and the subjects were instructed to "spell a word." The word to be spelled was not stated and it remained for the right hemisphere to recognize the individual letters and to arrange them into a meaningful order. Case 3 again proved able to do this and spelled such words as *cup*, *not*, *cake*, *love* and *what*.

Calculation

With stimuli presented tactually to the minor hemisphere through the left hand, Cases 2 and 3 demonstrated a limited ability to add correctly the numbers one or two to numbers under ten. They were unable, however, to subtract or multiply at this level. In this test, a set of from one to four wooden pegs (2·5 × ·8 cm.) implanted upright in two inch wooden blocks were presented to the patient's left hand, out of view and in

random order. Initially it was shown that the patients, upon command, could readily pick out blocks 1, 2 or 3, etc. With a card with printed numbers from 1–8 placed in open view in front of the patients, two blocks were serially presented to the left hand and the patients were required to point with the left hand to the number representing the sum. They usually succeeded with these numbers under five but were unable to subtract the number of pegs in one block from those in another or to double or triple the number of pegs.

All of the above tasks, of course, were performed easily with the other hand. In addition, much more complicated problems and general experience with the use of mathematics, changing money, estimating food quantities, etc. all made it questionable that calculations carried out with the major hemisphere were at all impaired. Case 3 had some difficulty during the fourth and fifth months after surgery in carrying out written mathematical calculations. This proved to be a problem not so much in the ability to calculate *per se*, but in taking care to scan far enough to the left so that all numbers fell in the right half field.

Discussion and Conclusions

Some of the main points that emerge here regarding the cerebral organization of language and the cerebral disconnexion syndrome generally, may be summarized briefly as follows. Information perceived exclusively or generated exclusively in the minor (right) hemisphere could be communicated neither in speech nor in writing; it had to be expressed entirely through non-verbal responses. By contrast, there was no noticeable impairment of speech and writing with reference to information processed in the major (left) hemisphere. Linguistic expression seemed, thus, to be organized almost exclusively in the left hemisphere. The possibility that a few simple emotional, tonal, or extremely familiar words might be expressed through the minor hemisphere in these cases, however, cannot be completely ruled out from the present data.

In tasks involving calculation the separated minor hemisphere was unable to multiply or divide even small numbers or items by two or by three, and subtraction of two or more from numbers below ten failed. Mathematical computations by the major hemisphere, on the other hand, were not markedly below pre-operative standards under optimal conditions where distractions were minimized and careful concern reinforced. Like speech and writing, calculation in these patients seems thus to be confined almost exclusively to the major hemisphere. This same hemisphere also, of course, was shown to process all visual functions for the right half of the visual field and the stereognostic functions for the right hand.

In contrast to the highly lateralized organization of verbal expression, the comprehension of language, both spoken and written, was found to be represented in the minor as well as in the major hemisphere. Present evidence indicates that the minor hemisphere is less proficient than the major in this respect, although the upper limits of language comprehension, ideation, and related activities in the minor hemisphere have yet to be determined. The minor, like the major hemisphere, was able to perform intermodal tasks such as the matching of tactually-perceived words and vice versa. Performances with the right hemisphere involving word and object association, sorting, retrieval and related tasks showed evidence of ideation, emotion, mental concentration and other high order mental capacities.

The observed ability to write with the left hand legible and meaningful material, though with rather poor penmanship, can be explained in terms of the bilateral motor control of both hands from the major hemisphere. Therefore it is not a contradiction of the above conclusion that writing is organized only in the major hemisphere. The bilaterality in motor control applies to a lesser degree to the control of the right hand from the minor hemisphere. This latter combination is clearly inferior to the above, in part because the dominant hemisphere tends to interfere more by imposing its own control on the right hand.

The foregoing applies also to the drawing of simple objects and geometric shapes perceived either visually or stereognostically. After presentation to the major hemisphere either hand could draw the object, but the performance was clearly superior with the right hand. Following such presentation to the minor right hemisphere, the left hand drew moderately recognizable reproductions. Drawing with the right hand, however, was highly erratic under these conditions and was commonly disrupted by interfering functions in the major hemisphere.

The general picture of the cerebral disconnexion syndrome that emerges from the present two cases would seem to stand somewhere well between the extremes arrived at by Akelaitis (1941; 1943; 1944) on the one hand and that outlined more recently by Geschwind (1962; 1965*a*, *b*). Whereas the results in our initial case conformed fairly well with the Liepmann-Geschwind interpretation, these more recent findings require a significant shift on a number of the important features of the disconnexion syndrome well over in the Akelaitis direction.

Though based on only two cases and clearly at variance with many reports in a literature filled with contradictions, there nevertheless are reasons at this time for thinking that the general picture as seen in these two individuals may represent, by and large, a common and perhaps the typical situation.

With respect to apraxia our present observations coincide rather closely with those of the Akelaitis series, and also with our own observations in subhuman primates. They favour the view that each hemisphere is able to direct the motor control of the ipsilateral, as well as the contralateral hand under normal conditions and also after pure commissural lesions. The appearance of apraxia or dyspraxia in connexion with long standing callosal lesions suggests, as concluded by Akelaitis, the presence of associated cerebral brain damage. The implication we would emphasize here, however, is not that the associated cortical damage itself is responsible, but rather that it is in most cases the combination of lesions that is critical. From recent evidence it appears that the ipsilateral control system in each cortex is delicate and easily deranged by minor damage that leaves the more robust contralateral system with little detectable impairment (Gazzaniga and Sperry, 1966).

The ipsilateral elements in the control system are not confined to the precentral region but are more diffuse. Also, good ipsilateral control is dependent on the functional integrity of the contralateral control system. And further, target references once established in an ipsilateral cortex are frequently bilateralized automatically or indirectly, thus allowing much of the final details of the motor patterning of co-ordination to be handled from the contralateral side (Gazzaniga, 1966). This complex of factors provides an interpretational scheme that seems to account for most of the data and conflicting observations in the experimental and clinical studies on apraxia following cortical and callosal lesions.

Our evidence that the disconnected minor hemisphere perceives and comprehends both the written and spoken word, as described earlier (Sperry, 1964; Gazzaniga, 1965; Sperry and Gazzaniga, 1965; Gazzaniga and Sperry, 1965) contrasts with previous reports of "word blindness" and "word deafness" following callosal lesions (Geschwind, 1962). Since the present two patients also appeared alexic and "word blind" in tests that involved verbal communication, one wonders if the application of appropriate non-verbal testing methods might not have demonstrated the presence of comprehension in the minor hemisphere in the earlier studies as well. Also the earlier cases of word blindness and deafness involved extensive cortical lesions in the dominant hemisphere. It becomes increasingly evident that the functional capacity of a unilateral cortical area with its contralateral counterpart intact may appear to be quite different from that seen in the presence of contralateral lesions. Allowing for considerable individual variation in the cerebral organization of language, the general picture as outlined in the present two cases could well prove to be more typical than exceptional so far as we can tell from the evidence now available.

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